# Science Case: Small PHA Potential Impactors

## Science Case justification and description

*Scientific Justification: briefly describe your science case, its scientific impact or broader impact, and the justification for the urgency of follow-up. (Max 300 words)*

The near-Earth object (NEO) small body population is vital for understanding Solar System formation and evolution, linking to the formation of exoplanetary systems, and for planetary defense. For the latter, the subset of NEOs with diameters *d* > 140 m and orbits that come within 0.05 au of Earth's orbit are traditionally referred to as Potentially Hazardous Asteroids (PHAs). There is good evidence, however, that the much more numerous smaller objects down to *d*~10 m pose a localized impact risk, from events such as the 500 kiloton-equivalent airburst produced by the *d*~17 m object that exploded over Chelyabinsk in 2013 Feb. These *d*~10-50 m objects are larger than the more frequent meteorite-dropping events commonly picked up by smaller-aperture facilities, which are not a priority for Rubin ToOs; they are also smaller than the traditional definition of PHAs, however, for this report, we refer to these objects as “small PHAs” to emphasize their potentially hazardous nature despite their smaller sizes.

Given that sky-plane uncertainties and rate of sky motions, which increase trailing losses, can increase very rapidly [1] within a few days of close-passing small PHA discovery, there is a need for Rubin ToOs on a limited subset of objects discovered that pose a potential threat to the Earth and for which follow-up would be impossible on other facilities (see Rubin-use justification below). A small fraction of these objects could be potential impactors coming from the sunward direction discovered by Rubin's near-Sun twilight microsurvey; these sunward-incoming small PHAs could require rapid-response Rubin ToOs before the discovery twilight period ends in order to confirm or rule out the possibility of impact before the object is no longer visible.

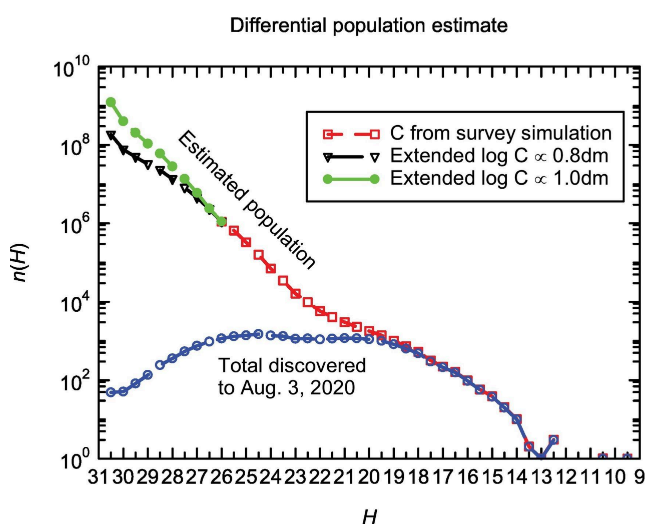


Figure 1 (from [2]): The differential population estimate of NEOs as a function of absolute magnitude H follows a steep power law, for which the normalization at the small-size end (26≲H≲31) has considerable uncertainty but will be substantially improved with Rubin and NEO Surveyor [3]. Rubin's etendue is 28x greater than the next-largest NEO survey facility, which will make Rubin the premier facility for discovering “small PHAs”.

*Justification for the use of Rubin: how and why are Rubin's capabilities uniquely suited to the follow-up of these targets (e.g. larger FoV and depth than DECam enable…) (Max 300 words)*

The Solar System ToO science case is unusual, perhaps unique, among those considered in that Rubin itself is extremely likely to be the prime trigger source for Rubin ToOs. This is due to the combination of a larger mirror diameter and larger field of view (4x and 7x the next-largest NEO survey telescope, respectively), location in the opposite hemisphere to the majority of other search assets, and near-Sun survey capabilities that give Rubin an unprecedented edge in the discovery space. Similarly, these same attributes make Rubin the only or most time-effective method of follow-up for small PHAs that exceed the capabilities of the 4-m Blanco+DECam or the 3.6-m CFHT+MegaCam (for objects discovered by Rubin that rapidly move into the Northern Hemisphere). We have been careful to write our trigger conditions below to exclude objects that are likely within the capabilities of these other two possible follow-up facilities (assuming suitable ToO observing modes and rapid pipeline processing facilities are available for Solar System ToO science cases on these non-Rubin facilities).

Rubin's unprecedented depth leads to discoveries of close-passing/potentially impacting small PHAs at much greater distances from Earth than existing NEO survey facilities can accomplish (see Fig 2 caption). Typically, close-passing/potentially impacting small PHAs are plagued by high rates of motion and increasing time since last reported detection, which both correspond to an increasing likelihood of newly discovered/short-arc object loss through a rapidly increasing ephemeris uncertainty and thus on-sky search area combined with increasing trailing losses over that search area that can exceed all possible capabilities at other facilities without rapid response observations (see Fig 2). For objects with a non-negligible impact probability, this can obviously be catastrophic without orbit-improving follow-up astrometry to remove the impact risk. Rubin's ability to detect these small PHAs at greater distances from Earth and reduce or eliminate their impact probabilities through rapid follow-up is thus required before the above issues become a problem, removing the ability of other facilities to perform the necessary impact-probability-reducing follow-up.

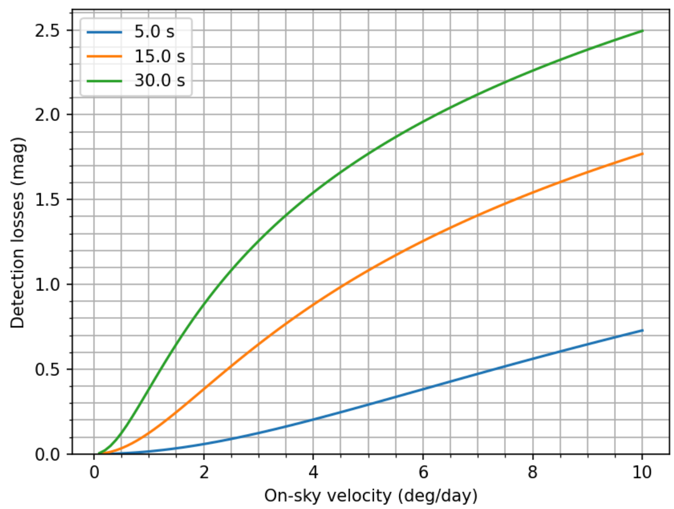


Figure 2: Decrease in detection depth due to motion-induced trailing losses (in magnitudes) for 30s (green, standard), 15s and 5s exposures as a function of on-sky velocity (in degrees/day). This assumes a typical r filter FWHM of 0.8". A study performed by the Asteroid Terrestrial-impact Last Alert System (ATLAS; a system of 4 x 0.5 m NEO survey telescopes) presented in [4] shows that H~25.4 (d~30 m) objects are visible to ATLAS at geocentric distances of up to 0.7 au (their Fig 8). Our preliminary analysis with modified metrics and extrapolated NEO population models (since the Rubin PHA model population based on [5] has no objects with H>25) suggests that Rubin will detect (5-sigma) H~28 objects at similar geocentric distances, ranging from 0.04-0.20 au [Lynne Jones, pers. comm]. (More in-depth modeling and "as-operating" measured values of Rubin's performance would be necessary to turn this into a true probabilistic detection volume perpendicular to and along Earth's orbit (e.g the "candle flame volume" of [4]'s Fig 8).) Based on a query of the JPL Small Body Database API[1], 30 H<28 confirmed NEOs passed within 1 lunar distance of the Earth from 2023 March - 2024 March. Generating ephemerides for Rubin for these 30 H<28 objects, we find an extremely broad range of magnitudes (V~20–31) at t-10 days before close-approach corresponding to the approximate center of the Rubin detection distance range above (0.04-0.20 au). (We have neglected the V-<filter> transformation here but [6] quotes V-g=-0.28, V-r=0.23, V-i=0.39, V-z=0.37 for a mean S+C NEO taxonomy for the very similar PanSTARRS filter system). This magnitude range obviously corresponds to very easy for Rubin (and other follow-up facilities) to impossible even with much deeper than standard Rubin exposure times. As the newly discovered NEO approaches Earth, it obviously increases in brightness but also in the on-sky rate of motion. Based on the ephemerides for the 30 H<28 objects described above, the range of motion at t-10 days before closest approach is 0.1 – 0.75 deg/day, which results in trailing losses of 0.006 – 0.25 mag (assuming r-band FWHM=0.8" and 30s exposures). At the time of closest approach, on-sky motion ranges from 10.9 – 650.7 deg/day with a median of 112.7 deg/day, well above the security-mandated maximum of 10 deg/day, which results in 2.5 mags of trailing loss.

[1] https://ssd-api.jpl.nasa.gov/doc/cad.html

*List a summary of the quantitative goals for the follow-up, including:*

- *Depth:* close-approaching or impacting small PHAs will be brighter than at the discovery epochs so the regular visit exposure times/single visit depth will produce better SNR and therefore better astrometric precision than the original discovery observations
- *Time frame(s) relative to trigger:* within the same local night (or twilight) as the trigger to the end of the following night
- *Area:* enough visits to cover the predicted ephemeris uncertainty at the time of observing
- *Bands: r* band for the maximum sensitivity and highest SNR for obtaining the astrometry required to most rapidly improve the orbit determination and decrease the impact probability. As a 2nd order optimization to minimize filter changes, it would be acceptable to execute observations in either of the red-sensitive bands (*iz*) if that filter were in position at the time of ToO execution. This would be particularly beneficial during the limited observing time available within the near-Sun twilight microsurvey.

*Suggested specific ToO observing strategies can be detailed below.*

## Target of opportunity activation criteria

*Describe when the ToO observations must be activated. E.g. if sky localization of the trigger is <X square degrees or >X square degrees, or what physical properties of the trigger should be considered. Describe how and by whom ToO candidates would be identified and communicated to Rubin. It would be most helpful and effective if you can write this down as a quantitative algorithm.*

ToO triggers for close-approaching or potentially impacting “small PHAs” would occur based on the JPL Scout alerts[2] (for newly-discovered/short arc objects from Rubin or other surveys) or Sentry alerts[3] (for objects with longer (multi-year) arcs that have updated orbits and newly increased impact probabilities) that have specific conditions; these conditions are listed below and would need to be extracted from the Scout alert information, which is in JSON format.

We would trigger a Rubin ToO for a close-approaching or potentially impacting “small PHA” under the following conditions:

- $H<28$ (corresponding to diameter $d>10$m assuming albedo=0.15)
- Earth close approach distance < 1 Lunar distance (LD; limits Rubin ToO time to not trigger on non-threatening objects that are projected to pass by at much larger distance; also the rate of potential triggers increases greatly with increased radius)
- Cumulative impact probability > 10^-3
- Low likelihood that the object is in a geocentric orbit
- Predicted magnitude $V>21.6$ and ephemeris uncertainty >1 sq. deg (Northern Hemisphere) or $V>21.8$ and ephemeris uncertainty > 3 sq. deg (Southern Hemisphere) at $T$+24 hours from the time of the Scout/Sentry alert
- No community ToO follow-up programs exist for the current semester on community non-Rubin assets, attempts to recover with other facilities have not been successful, and searches for <5-sigma detections from any existing LSST observations have not been successful

[2] https://cneos.jpl.nasa.gov/scout/intro.html
[3] https://cneos.jpl.nasa.gov/sentry/

    - If a follow-up program on a facility such as Gemini South or ESO VLT is granted time to observe a Rubin ToO target, the Rubin ToO could be paused; although this would be difficult to do programmatically and would likely require a human to be part of the trigger decision process
    - Likewise, if the Rubin SSP team found the object in the <5-sigma Rubin detections, the Rubin ToO could be paused
- Object unlikely to be detected in the natural course of LSST observations
- Apparent sky-plane rates of <10 deg/day (This is an externally imposed restriction on Rubin processing for national security considerations (DMTN-199) but excludes most targets that are within ~1 LD and within a few days of close-approach.)
    - Rubin's unprecedented depth leads to discoveries of close-passing NEOs at much greater distance than e.g. 0.5-m ATLAS, allowing removal of the risk of impact at greater distances when it can't be followed up with smaller facilities. This circumvents the issue of trying to chase rapidly accelerating objects (which could exceed the Rubin 10 deg/day limit and have increased trailing losses) and that have growing uncertainty regions that could overwhelm smaller FoV facilities

The above information would come from the JPL Scout alerts (for newly-discovered/short arc objects) or Sentry alerts (for objects with longer (multi-year) arcs that have updated orbits and newly increased impact probabilities) that are updated and resent after the receipt and processing by the MPC and JPL of new observations from either Rubin or other follow-up facilities. The most recent alert will thus always contain the most up-to-date information, and therefore it is relatively easy to avoid a trigger or re-trigger of a Rubin ToO when an updated object would no longer pass the trigger criteria (primarily the impact probability and/or the ephemeris uncertainty) defined above. These alerts would need to be obtained through API calls developed by the Rubin Project to process and analyze the Scout and Sentry alerts and trigger Rubin ToOs programmatically. To ensure that the executed triggers are indeed valuable, we request that a human be kept in the ToO trigger loop, especially early on in science operations as we understand the false positive rate produced by early Rubin discoveries; the LSST SSSC NEOs+ISOs Working Group can commit to having someone on call who can reply to emails from the observer before triggering a ToO on a close-passing/potentially impacting "small PHA" coming from a JPL or Sentry alert. The NEOs+ISOs WG would also monitor the trigger performance to assess metrics such as the overall rate of Rubin ToO triggers and the false positive rate.

## Time Budget:

*If multiple strategies are outlined for the same science case, please include tradeoffs between strategy requirements, number of targets, scientific returns, etc…*

The close-approaching small PHAs from the twilight survey follow the same criteria and require the same follow-up as the regular close-approaching small PHAs case, so no trade-offs are necessary (beyond implementation details for Project on potentially needing to trigger ToOs during twilight time).

## Search Area (sq deg)

Min:  >5' (set by the smallest FoV of Gemini+GMOS-S and VLT+FORS2 for objects with V>22 which are too faint + rapidly moving to be recovered using 4m telescopes + 1-3 sq. deg imagers)

Max: few 10's of sq. degrees

Typical: < 1-5 degrees

## Event rate (triggers/year)

Min: 1

Max: 30 (rates are very difficult to estimate since Rubin is so much larger and more sensitive than existing NEO surveys and the characteristics of the orbit quality and timescale of new close-passing NEO discoveries from Rubin (3 pairs of detections over a ~15 day period with each pair separated by 33 minutes producing a confirmed new object) than existing NEO surveys (3-4 images over ~40 minutes with confirmation of NEO nature & orbit refinement from other facilities) that prior precedent on rates is of limited use. This rate is based on the statistics of known close-approachers from the JPL Small Body DB which is known to be biased low due to the absence of search assets for fast-moving small NEOs before Rubin. In addition, in order to be a close-approaching NEO and in the SBDB, they have to (by definition) be non-impacting. However we have no access to the time-evolution of the impact probability as a function of time and amount of follow-up observations from the Scout alerts which is what we really need, in conjunction with a better estimate of the rate of small close approachers, to determine a more accurate rate of need for Rubin ToOs. This number will be better understood after Year 1 of Rubin science operations.

## Max delay from trigger (hours)

*Include a discussion of how the science return changes as the delay between the initial trigger and time of observation increases.*

Ideally observations commence within an hour of receipt of the ToO trigger. The uncertainty region and on-sky rate of motion will grow with increasing time delay from the trigger, leading to an increased chance of not being able to recover the object or link the observations to the existing object.

## Trigger time distribution or constraints

*e.g.: during LVK runs, more when new facilities come online, only at twilight, etc.*

The trigger could occur within a few tens of minutes to a few days of initial detection or discovery by Rubin or another survey. The urgency is set by a combination of factors, namely:

- the predicted close approach distance and associated uncertainty on this particular close approach,
- the cumulative impact probability accumulated over current and future close approaches to the Earth,

- the predicted magnitude and size of the uncertainty region at T+24 hours after the alert trigger,
- the absolute magnitude and therefore the estimated diameter and impact energy were the object to potentially impact.

Close-approaching "small PHAs" are not known to have any preferred direction or occurrence time for objects of the size range under consideration. Objects detected in the near-sun twilight survey will only be able to be followed in twilight. Small PHAs discovered by Rubin to be on a potentially-impacting trajectory coming from the sunward direction found during twilight will require ToOs to be rapidly triggered and executed before that twilight period ends and the object is no longer visible in order to confirm or rule out the possibility of impact.

### Non-standard observing requests (e.g., exposure times != 30s, dynamic depth, trailing)

PLEASE NOTE: While it is expected that longer or shorter exposures than the standard 30 seconds will be possible, the range of exposures that can be supported and processed by the standard pipeline will not be defined until commissioning. The feasibility of non-standard observations cannot be guaranteed and no special processing will be supported at the start of the program. This includes: alert production will not be able to provide on-the-fly coaddition of multiple standard visits to achieve greater depth.

Because non-standard observations cannot be guaranteed and no special processing will be supported at the start of operations, we do not request exposure times != 30 s. Since Rubin's unprecedented depth will lead to discoveries of close-passing/potentially impacting small PHAs at much greater distance from Earth than existing NEO survey facilities are able to accomplish, constrained as needed by Rubin ToOs, the risk of impact will be removed when objects are at greater distances from Earth, circumventing the issue of trying to follow-up rapidly accelerating objects that could lead to increased trailing losses. This should result in 30 s exposures that do not lead to significant trailing losses for Rubin ToOs. Additionally, the lack of support for rapid processing of exposure times != 30 s would make it difficult to execute a triggered ToO rapidly as would be required for small PHAs discovered by Rubin to be on a potentially-impacting trajectory coming from the sunward direction found during twilight that must be followed-up before that twilight period ends and the object is no longer visible in order to confirm or rule out the possibility of impact. Finally, using the standard 30 s exposure time will allow any Solar System ToOs executed during the regular nightly survey cadence to be folded back into the WFD observations, limiting the disruption and diminishing of the full survey caused by ToOs.

## Observing Strategy Details

*Ideally, this would include depth to be achieved in each band, number of repeated observations, and time gaps between observations, justified by physical parameters of the triggers.*

*Does your science case require observations after the first night of ToO activation (day 0)? If so, justify why.*

No. Although subsequent observations may be required to obtain orbit-improving astrometry and colors for characterization, these can be carried out as part of the regular Rubin survey or with other dedicated facilities and don't require Rubin ToOs.

Day 0:

For pure astrometry, *r* band exposures are requested. We require 3 epochs of observation centered on the predicted asteroid position at the time of the exposure. The epochs should be separated by ~33 minutes and include 2 exposures with a dither.

For astrometry to improve the orbit and reduce the probability of impact, we need detectable measurements from three to four epochs on the same night. Due to the active area fraction of 90% in the LSST Camera, we ask for the telescope pointing to be dithered between the two exposures in an epoch in order to reduce the risk of these fast-moving objects disappearing in an inactive area or chip gap.

number of Observations per filter: 6

Total time:

- Slew/settle, Setup and filter change: 15 sec (slew/settle; worst case) + 120 sec filter change = 135 sec setup (assuming no overlap of slew & filter change)
- 2x15 sec integrations + 2x2 sec (readout) + 3 sec (dither/settle) overheads = 37 sec per exposure
- Total = 135 sec + 6x37 sec = 357 sec total sequence time (0.099 hours)

Worst case scenario of 30 triggers/year: Total time = 2.98 hours/year

This calculation above is for dark time. If the only time to observe the small PHA is in twilight, then the exposure should be reduced to 15 sec (or whatever is suitable for the sky background) using the *z*-band filter, like the near-Sun twilight microsurvey.

## Special Observing Requests and Data Processing Requirements

Please note: Specialized data processing pipelines for the ToO program are not supported in the current plan: the ToO data will be processed through the Rubin standard data processing pipeline. Please describe how you will use standard DM products to accomplish your science. If your data requires special processing please include what resources are available to your community to ensure its feasibility. Clearly describe the potential impact if the observations must be done with standard processing.

The standard DM products from the 2x15s exposures combined to single 30s exposure (or 1x30s if adopted) of accurate astrometric positions, precise exposure timing and accurate magnitudes, combined with the normal reporting channels to the Minor Planet Center will be sufficient for this science case. In some situations this may require some intervention by the Rubin SSP team to pull out the associated observations such as manual access to the pixel data inside the 80 hour limit or accessing the linked tracklets SSP has identified from the given night.

## Downscoping direction suggestions

*The SCOC will engage in a global optimization exercise over the full scope of the LSST, including the ToO program. Simulations of LSSTs that include ToO programs based on your suggestions will reveal the cost of the ToO program to the other LSST science goals and enable* *the SCOC to make a recommendation for time to be allocated to ToOs. In this section, please share recommendations for sensible ways to downscope your proposed ToO program if needed, including the impact of reducing the number of targets, filters, or epochs.*

As discussed above under the rates, the predicted rates of triggers are hard to estimate given the lack of precedent from existing surveys (opposite hemisphere, shallower depth, smaller FoV as discussed previously) but options for limiting the rate if it is judged to be excessive could include:

1) raising the threshold on impact probability, resulting in fewer triggers,
2) raising the absolute magnitude (*H*) cutoff to smaller values (larger object diameters) and therefore using ToO triggers on objects that have a higher risk of more significant damage,
3) increasing the time threshold after discovery but before triggering Rubin ToOs in the hope that other facilities that are observing at the same time i.e. Blanco+DECam/CFHT+Megacam (since there is a lack of deep+wide field capabilities at ESO or other Southern Hemisphere longitudes) are able to perform the initial recovery first

We also request that this ToO program only begin after the first 3 months of Rubin science operations in order to assess both the PHA impactor false positive rate and event rate when the influx of Rubin discoveries begin to populate the JPL Sentry Earth impact monitoring table.

**References**


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[2] Harris, A. W. & Chodas, P. W., Icarus, 365, 114452 (2021) doi: 10.1016/j.icarus.2021.114452
[3] Mainzer, A. K., Masiero, J., R., Abell, P. A. et al. PSJ, 4, 224 (2023) doi: 10.3847/PSJ/ad0468
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[5] Granvik, M. Morbidelli, A., Jedicke, R. et al., Icarus, 312, p. 181-207 (2018) doi: 10.1016/j.icarus.2018.04.018
[6] Vereš, P. et al., Icarus, 261, 34 (2015) doi: 10.1016/j.icarus.2015.08.007

# Science Case: Future Interesting Twilight Discoveries

## Science Case justification and description

*Scientific Justification: briefly describe your science case, its scientific impact or broader impact, and the justification for the urgency of follow-up. (Max 300 words)*

Rubin's near-Sun twilight microsurvey will offer the opportunity for Rubin to observe the low-SE sky during twilight, which is the only time when viewing Solar System objects inward to Earth is possible. Near-Earth objects (NEOs) interior to Earth's orbit (including Atiras with orbits interior to the orbit of Earth and 'Ayló'chaxnims (or inner-Venus asteroids) with orbits interior to Venus) are the least constrained portion of currently available NEO models owing to observational limitations of objects at low SE [1,2]. In addition, the near-Sun twilight microsurvey could enhance the discovery of interstellar objects (ISOs); ISO 2I/Borisov was discovered during twilight by an amateur astronomer in 2019 [3]. Characterizing these interstellar visitors, including obtaining photometric colors, light curves & rotation periods, as well as possible mass shedding, outbursting, or breakup events provides a unique opportunity to help put our Solar System in context with other exoplanetary systems.

Some inner-Venus asteroids detected in Rubin's near-Sun twilight microsurvey could have large enough ephemeris uncertainties to become lost behind the Sun if not rapidly recovered by triggering a Rubin ToO during twilight hours. Likewise, some ISOs may have exceptionally limited observing windows/geometry before becoming too faint as they leave the Solar System that would require Rubin ToO follow-up before the unique opportunity to observe and characterize these interstellar visitors disappears.

However, due to a number of uncertainties, largely stemming from the current small sample sizes for these two populations (to date, one inner-Venus asteroid and two ISOs have been discovered), we have chosen not to pursue this science case in the current Rubin ToO proposal round. It's unclear whether the astrometric uncertainties for these population discoveries would warrant triggering Rubin ToOs, and thus the event rate for Rubin ToO triggers for these objects is also largely uncertain. The near-Sun twilight microsurvey should increase discoveries of both inner-Venus asteroids and ISOs, however, it will likely remain unclear how many objects may need rapid follow-up from Rubin and under what conditions that follow-up would need to be conducted until after the first year of the survey has been completed. At that time, we should have a better understanding of the discovery rates and the need to trigger Rubin ToOs for these populations. We may thus want the opportunity to request Rubin ToOs for this science case after Year 1 of the survey has been completed when the next round of Rubin ToO proposals are considered.

**References**


[1] Greenstreet, S., Ngo, H., Gladman, B., Icarus, 217, 355 (2012)
[2] Granvik, M., Morbidelli, A., Jedicke, R., et al., Icarus, 312, 181 (2018)
[3] Borisov, G., Minor Planet Electronic Circular, MPEC 2019-R106, https://www.minorplanetcenter.net/mpec/K19/K19RA6.html (2019)